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Standard Guide for Additive Manufacturing — Design — Decision Support¹

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1. Scope

1.1 This document's purpose is to guide designers who are considering the use of metal, polymer or ceramic Additive Manufacturing (AM) for their products. Section 4 outlines the technical and commercial opportunities of AM, supported with examples; it focuses on applications rather than specific processes or technologies. Section 5 considers the available AM process categories and materials, with comparisons of their capabilities. Section 6 offers advice from a designer's perspective on evaluating AM as a manufacturing solution. It also identifies other considerations from the AM process chain that would affect a decision on whether to adopt AM.

1.2 This guide aids in the initial decision as to whether AM is a suitable process for a given product. It is intended as a complement to the more specific product design information contained in ISO/ASTM 52910.

1.3 The following AM processes are not considered in this guide:

- 1.3.1 Processes that have developed from coating methods, for example cold spray,
- 1.3.2 Direct write technologies,
- 1.3.3 Nano-AM technologies,
- 1.3.4 Biomaterial-focussed processes and bioprinting applications, and

1.3.5 Processes and materials that are used to directly build items specific to the construction sector, for example material extrusion-based concrete items.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recom-*

mendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 ASTM Standards:²

- F2971 Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
- F3091/F3091M Specification for Powder Bed Fusion of Plastic Materials
- F3122 Additive manufacturing — General principles — Main characteristics and corresponding test methods
- F3187 Guide for Directed Energy Deposition of Metals
- F3213 Additive Manufacturing – Finished Part Properties – Standard Specification for Cobalt-28 Chromium-6 Molybdenum via Powder Bed Fusion
- F3301 Additive Manufacturing – Post Processing Methods – Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion
- F3302 Additive Manufacturing – Finished Part Properties – Standard Specification for Titanium Alloys via Powder Bed Fusion
- F3318 Additive Manufacturing – Finished Part Properties – Specification for AlSi10Mg with Powder Bed Fusion – Laser Beam

2.2 ISO/ASTM Standards:²

- 52900 Additive manufacturing — General principles — Fundamentals and vocabulary
- 52901 Additive manufacturing — General principles — Requirements for purchased AM parts
- 52902 Additive manufacturing — Test artefacts — Geometric capability assessment of additive manufacturing systems
- 52904 Additive manufacturing – Process characteristics and performance: Practice for metal powder bed fusion process to meet critical applications
- 52909 Additive manufacturing of metals — Finished part properties — Orientation and location dependence of mechanical properties for metal powder bed fusion

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² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at www.astm.org/contact. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

52910 Additive manufacturing — Design — Requirements, guidelines and recommendations

52911-1 Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals

52911-2 Additive manufacturing — Design — Part 2: Laser-based powder bed fusion of polymers

3. Terminology

3.1 *Definitions:* For the purposes of this guide, the terms and definitions as per ISO/ASTM 52900 and the following terms and definitions apply:

3.1.1 *debind*, *v*—remove binder material.

3.1.2 *laser spot size*, *n*—diameter of beam at the top of the build surface.

3.1.3 *layer thickness*, *n*—nominal height of each layer (or ‘slice’).

3.1.4 *overhang*, *n*—a condition where a section of a layer projects or extends beyond the geometry in the previous layer.

3.1.5 *topology optimization*, *n*—a computer driven mathematical based modelling technique, which outputs an optimal solution given a set of loads and constraints.

3.2 *Abbreviations:*

3.2.1 *ABS*—acrylonitrile butadiene styrene

3.2.2 *ASA*—acrylonitrile styrene acrylate

3.2.3 *CNC*—computer numerical control

3.2.4 *DfAM*—design for additive manufacturing

3.2.5 *DfM*—design for manufacture

3.2.6 *DLP*—direct light processing

3.2.7 *EPU*—elastomeric polyurethane

3.2.8 *MOQ*—minimum order quantity

3.2.9 *OEM*—original equipment manufacturer

3.2.10 *PA*—polyamide (nylon)

3.2.11 *PC*—polycarbonate

3.2.12 *PEEK*—polyetheretherketone

3.2.13 *PEI*—polyetherimide

3.2.14 *PET-G*—polyethylene terephthalate glycol

3.2.15 *PLA*—polylactic acid

3.2.16 *PMMA*—poly(methyl methacrylate)

3.2.17 *PPSU*—polyphenylsulfone

3.2.18 *RDM*—redistributed manufacturing

3.2.19 *ROM*—rough order of magnitude

3.2.20 *TPU*—thermoplastic polyurethane

4. Overview of Additive Manufacturing Applications

4.1 AM processes are characterized by a construction method that does not make use of a forming tool, thereby allowing almost unrestricted geometry for each layer of the object that is being made. In theory, this should allow any object to be manufactured by AM, without the manufacturing restrictions and the lead times and use of tools, tooling, jigs or fixtures. Although there are limitations in practice (described in 6.2.1.1), unrestricted geometry is a foundational principle

when designing for AM. This section gives examples of how the opportunity can be used to obtain benefits compared with other manufacturing methods. It is split into two sections, the first section being examples of direct benefits, that is, where AM can create a product that is better than its conventional equivalent, in terms of performance or market reach. The second section gives examples of indirect benefits that AM offers, for example savings in time to market or manufacturing cost and complexity.

4.2 *Examples of Direct Benefits of Using AM:*

4.2.1 *Functional Benefit:*

4.2.1.1 *Optimization of Performance*—Designers are using AM to improve the effectiveness of components, for example by:

(1) Optimizing load paths to reduce the amount of material used in structural components.

(2) Improving fluid and heat flows and therefore the efficiency of pumps, heat exchangers or heat sinks.

(3) Tuning the energy absorption of structures.

4.2.1.2 Examples of performance benefits are shown in Figs. 1-5. Each example illustrates a functional benefit that AM has enabled. The captions explain what the component is and the reason it was made using AM.

4.2.1.3 *Functional Integration*—The relaxed restrictions on geometry allows integration of previously disparate functions. In the example in Fig. 6, the suction function for cleaning computer chips is achieved while incorporating the connector and flow channels for an ionizing airflow that was a separate component in the original design.

4.2.1.4 *Custom Fit*—A specific application of AM for functional improvement is through custom fit products, taking advantage of the digital nature of AM by feeding customer raster data into the design process. Fig. 7 shows an example of a custom-fit mandible (jaw) implant.

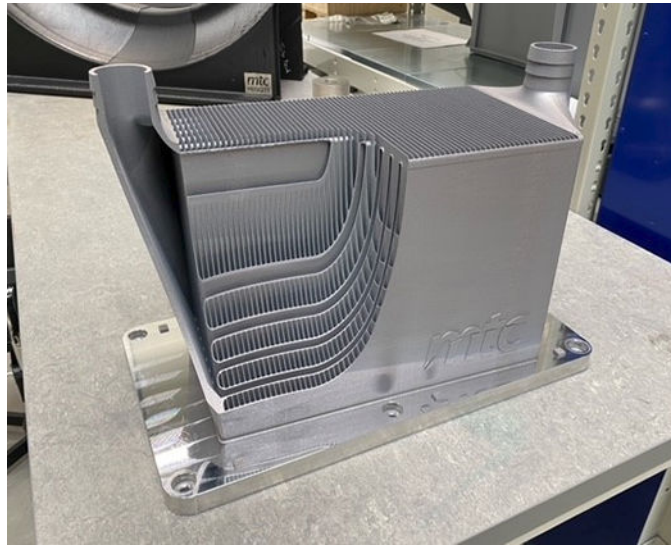
4.2.1.5 *Monolithic Mechanisms*—AM is being used for monolithic mechanisms or other structures that change shape. An example of this is a compliant or flexural mechanism as shown in Fig. 8. Compliant mechanisms have multiple performance benefits, for instance zero backlash and no friction from moving joints. Simple devices such as ‘living hinges’ can be manufactured conventionally but AM allows more complex implementations.

4.2.2 *Other Product Design Benefits:*

4.2.2.1 *Part Consolidation*—AM can be used for products that were formerly made in sections and then assembled because of geometric constraints of the manufacturing process. A direct benefit of this would be size and material reduction since joint interfaces are not needed, as illustrated by the waveguide in Fig. 9. Also refer to section 4.3.1.2 for the indirect benefits that part consolidation offers.

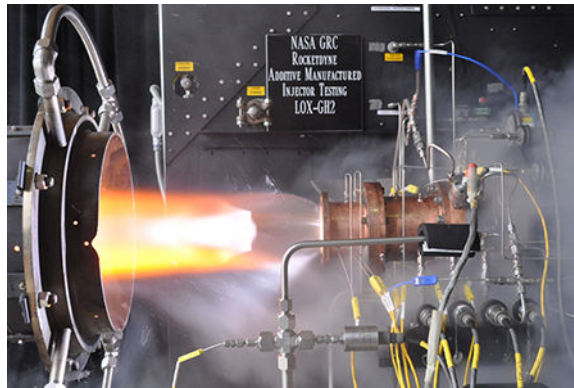
4.2.2.2 *Multicolor and Multimaterial*—Several AM processes provides multi-color solutions for AM with applications in many industries including education, manufacturing, geospatial, architecture, the arts and entertainment. The high fidelity color on the topographic model in Fig. 10 greatly enhances model visualization.

4.2.2.3 Some processes allow multiple materials to be combined in a single build. Fig. 11 shows a single printing



Material:	Aluminium (AlSi10Mg)
Company / credit:	Manufacturing Technology Centre
Industry sector:	Multiple
Why AM was used:	Allows conformal shape, very high surface area
Potential secondary benefits:	Streamlined manufacturing process
Which AM process:	PBF-LB/M
Other suitable AM process categories:	BJT-MSt/M potentially

FIG. 1 Heat Exchanger (© MTC, all rights reserved)



Material:	Unspecified alloy
Company / credit:	Aerojet Rocketdyne
Industry sector:	Space
Why AM was used:	Reduced part count, component efficiency
Potential secondary benefits:	Less weight, fewer fasteners, fewer end-to-end production hours, design flexibility
Which AM process:	PBF-LB/M
Other suitable AM process categories:	Any metal-based processes for high temperature alloys

FIG. 2 Rocket Motor Fuel Injector (© Aerojet Rocketdyne, all rights reserved)

aid model of an organ. Different features of the organ are highlighted through the use of separate opacities, colors and materials.

4.2.2.4 It is worth noting that, generally speaking, graded color or material support relying on volumetric texturing is partially supported or completely unsupported by most standardized Additive Manufacturing Design Data Exchange For-

mats and so relies on either slicing directly from the design software or the support software package provided by the equipment supplier.

4.2.2.5 *Ornamental Complexity*—Artists and fashion designers have investigated the creative opportunities afforded by AM. The jewellery piece shown in Fig. 12 is an example.



Material:	Silicon Nitride
Company / credit:	Lithoz GmbH
Industry sector:	Automotive, Energy
Why AM was used:	Reduced inertial force (and therefore lag) due to use of ceramic instead of metal. Only AM can create the geometry in a ceramic material.
Potential secondary benefits:	Higher resistance to heat exposure from use of ceramic instead of metal
Which AM process category:	VPP-MSt/C
Other suitable AM process categories:	BJT-MSt/C (would require Si ₃ N ₄ development for process)

FIG. 3 Ceramic Impeller (© Lithoz GmbH, all rights reserved)



Material:	Assorted polymers used for formwork
Company / credit:	Xijie Ma, Digital Building Technologies, ETH Zürich
Industry sector:	Construction
Why AM was used:	AM was used for the formwork. This enabled a freeform, more efficient floor structure, which reduced material use and weight.
Potential secondary benefits:	Reduced loads on other structural elements of building due to lighter floors.
Which AM process category:	BJT and MEX
Other suitable AM process categories:	Processes chosen based on material processed and scale of components

FIG. 4 Concrete Flooring (© DFAB HOUSE, n.d.)

4.2.2.6 *Novel Products*—In the example shown in Fig. 13, the product – an antennae lens – is enabled by AM, since there are no other commercially viable ways to manufacture high value, high gain, wide bandwidth, low loss millimeter and

microwave lenses. (Note on image: The lens is an assembly of 6 pieces. An example of one of the pieces sits in the foreground of the image.)

4.2.3 *Commercial Benefit:*



Material:	Ultrasint® TPU 01
Company / credit:	BASF Forward AM
Industry sector:	Transportation
Why AM was used:	Localised tuning of the component's damping response
Potential secondary benefits:	Customisation, Aeration, Comfort, Aesthetics
Which AM process category:	PBF
Other suitable AM process categories:	MJF or SLS, subject to suitable material availability

FIG. 5 Elastomeric Motorbike Saddle Designed for Energy Absorption (© BASF/Forward AM)



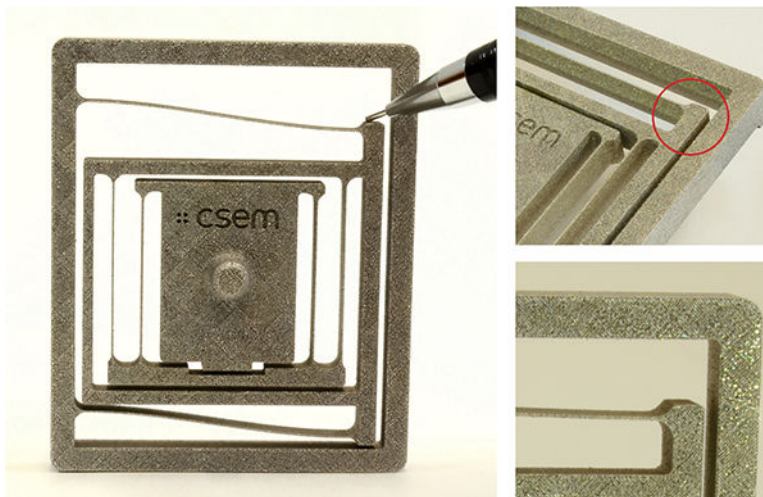
Material:	Stainless steel 316L
Company / credit:	IRPD AG & INSPIRE Switzerland
Industry sector:	Electronics
Why AM was used:	Complex geometries required
Potential secondary benefits:	Integration of the electrostatic discharge ioniser in the same component
Which AM process:	PBF-LB
Other suitable AM process categories:	A metal AM process with high resolution, for example BJT-MSI/M

FIG. 6 Suction Cup for Computer Chips (© IRPD AG/INSPIRE, all rights reserved)



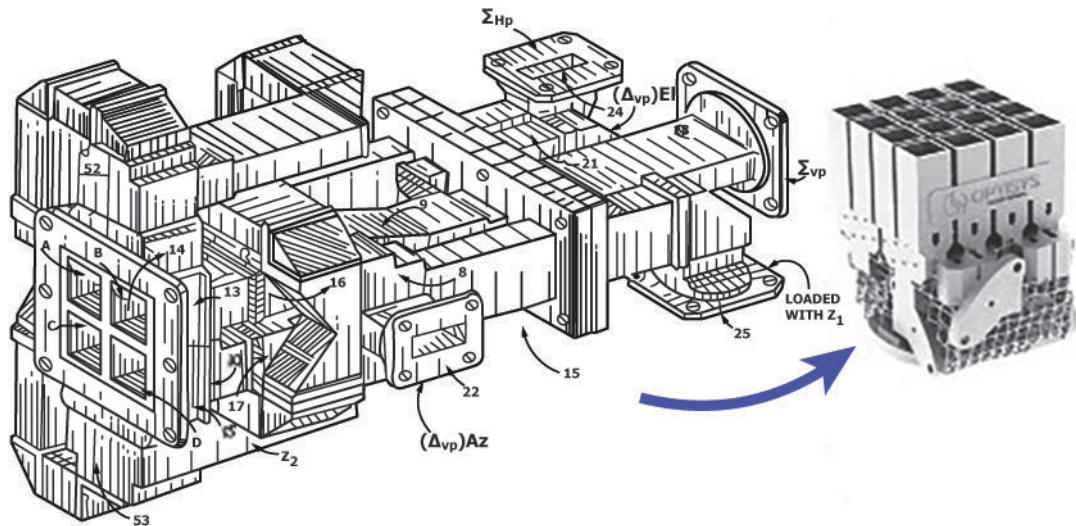
Material:	Ti alloy
Company / credit:	Porous application by Sebastiaan Deviaene
Industry sector:	Medical
Why AM was used:	Custom fit offers better customer experience
Potential secondary benefits:	No need to make and stock multiple standard sized parts for surgeon to choose from
Which AM process:	PBF-LB
Other suitable AM process categories:	Any that can process a biocompatible alloy

FIG. 7 Jaw Implant (Sebastiaan Deviaene)



Material:	Stainless steel 316L
Company / credit:	CSEM Switzerland
Industry sector:	Any
Why AM was used:	Complex compliant mechanisms enabled by lack of tooling constraints
Potential secondary benefits:	Fast iterations while optimizing the design
Which AM process:	PBF-LB
Other suitable AM process categories:	BJT-MSI/M

FIG. 8 Linear Stage Compliant Mechanism (© CSEM)



Material:	Unspecified alloy
Company / credit:	Optisys, Inc.
Industry sector:	Communications
Why AM was used:	Reduces overall size since no interfaces between parts
Potential secondary benefits:	Part consolidation, reduced production assembly time, logistics, quality control
Which AM process:	PBF-LB
Other suitable AM process categories:	BJT-MST/M

FIG. 9 Waveguide (Optisys, Inc.)



Material:	Resin
Company / credit:	Hybrid Services Ltd.
Industry sector:	Architecture
Why AM was used:	The ability to print in full color on the surface
Which AM process category:	MJT
Other suitable AM process categories:	BJT with colored binder

FIG. 10 Full Color Architectural Models (created with Mimaki 3D printer)

4.2.3.1 Time to Market:

(1) *Design Iterations*—Through use of AM prototypes, designs can be iterated fast, reducing the time to reach design freeze.

(2) *AM Tooling*—Castings, mouldings and forgings require tooling lead time, so AM may offer a lead time reduction by:

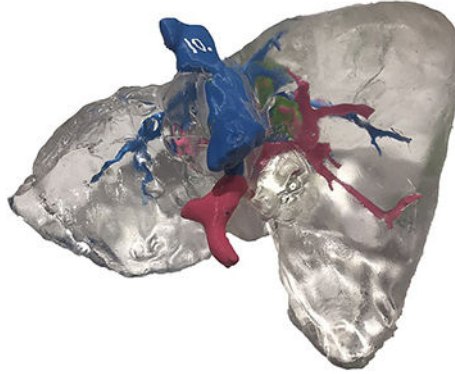
(a) Manufacturing the tool itself.

(b) Manufacturing polymer or metal bridge tooling fast, to be used until production tooling is available.

(c) Avoiding the need for a tool altogether for low production quantities.

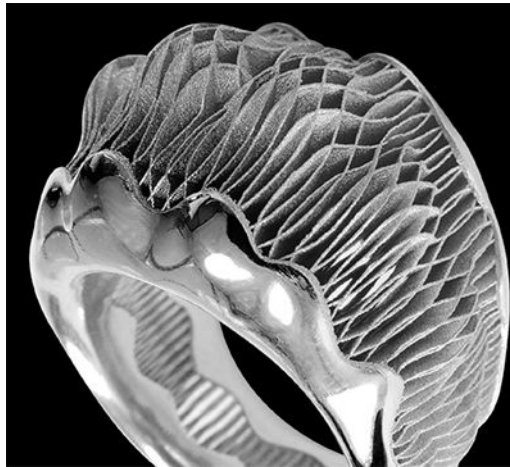
(3) Using AM to manufacture the tool also means that tool design can be iterated with less impact on lead times. A composite tooling example is shown in Fig. 14. Fig. 15 shows an example of a sand casting tool that was fabricated in a sand-based material.

(4) More and more composite polymer AM materials are becoming available which provide conductive fillers to



Material:	Photosensitive resins
Company / credit:	Creative Commons
Industry sector:	Medical
Why AM was used:	To enable surgical planning by using patient scan data
Which AM process category:	MJT
Other suitable AM process categories:	Currently, MJT is the only process family to mix opaque and clear materials in a single build.

FIG. 11 Multimaterial and Multicolor Surgical Planning Aid (image credit: Creative Commons)



Material:	Gold
Company / credit:	NuoviGioielli
Industry sector:	Consumer
Why AM was used:	Unique form
Which AM process category:	VPP to create a wax pattern for investment casting
Other suitable AM process categories:	Any AM process that processes precious metals and has high resolution could be used, although if surface texture is important, indirect use of a polymer AM process to make a master for a metal casting mould might be more suitable.

FIG. 12 Jewelry (© NuoviGioielli, all rights reserved)

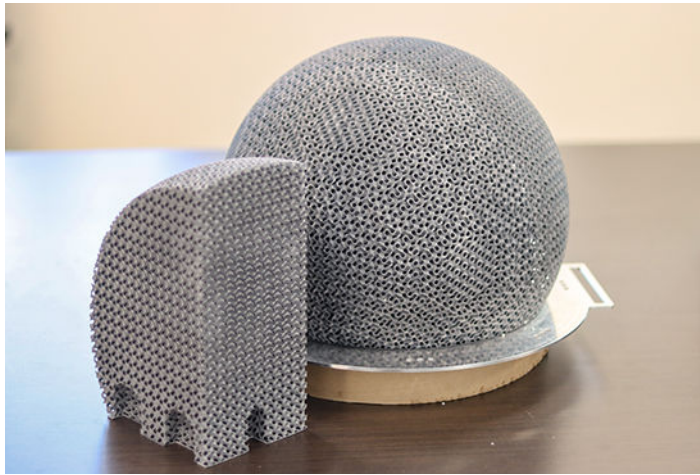
properties, opening up the possibilities of replacing traditional metallic tooling with cheaper polymer variants.

(5) AM is also used for disposable tools, for example investment casting patterns (an example is shown in Fig. 12).

4.2.3.2 *Product Variations*—The digital nature of AM and the absence of tooling facilitates the manufacture of product batches where each batch is differentiated from the previous one. It is therefore possible to easily tweak the design of a single product and create variants, one of which is shown with the shipping case in Fig. 16.

(1) *Mass Customisation*—Taken a step further, individual products can also be made to order in response to a customer's preference being input at the design stage. The personalized spectacles shown in Fig. 17 are an example.

4.2.3.3 *Service Life*—Product life can be improved to give a product a competitive advantage that justifies a higher price, offsetting the additional cost of manufacturing by AM. The induction coil in Fig. 18 achieves more consistent wall thickness than a conventional wound coil, resulting in longer service life.



Material:	Rogers Radix 2.8Dk Printable Dielectric
Company / credit:	Fortify
Industry sector:	Satellite Communications / Radiofrequency Antennas
Why AM was used:	Gyroid based lattice geometries are necessary for the realization of a Gradient Refractive Index lens.
Potential secondary benefits:	—
Which AM process:	VPP
Other suitable AM process categories:	MEX has been used, but currently available throughput and resolution make it suitable for prototyping only

FIG. 13 Switched Beam Array Antenna Lens (3-18 GHz) (© Fortify, all rights reserved)



Material:	Unspecified polymer
Company / credit:	Thermwood/Boeing
Industry sector:	Aerospace
Why AM was used:	Lead time and iteration time is reduced
Potential secondary benefits:	Cost reduction
Which AM process category:	Large scale MEX
Other suitable AM process categories:	Currently no other suitable polymer-based processes at this size

FIG. 14 Large Scale AM Polymer Tooling (image provided by Thermwood)

4.2.3.4 *Legacy Components*—Components that are no longer in stock and have no engineering drawings or necessary tooling, or both, can be recreated with an AM equivalent, as illustrated by the inlet manifold shown in Fig. 19.

4.3 Indirect Benefits of Using AM:

4.3.1 Manufacturing Steps:

4.3.1.1 *Fabrication*—Fabrication methods can often require complex jigs and require multiple quality control steps, so a single AM component in place of a fabricated assembly may simplify the quality control process as well as the time and cost.



Material:	Sand, with a phenolic resin binder
Company / credit:	Voxeljet
Industry sector:	Any
Why AM was used:	Fast, economic tooling
Potential secondary benefits:	Complex geometries, fast iterations
Which AM process category:	BJT
Other suitable AM process categories:	–

FIG. 15 Sand Tooling (© Voxeljet)

need to manufacture jigs and fixtures. This idea is illustrated well by the exhaust manifold merge collector shown in Fig. 20.

4.3.1.2 Part Consolidation, Mechanisms and Assemblies-in-One—The use of part consolidation (4.2.2.1) has the added benefit of reducing the manufacturing process steps and inspection points, as well as reducing energy consumption when compared to making and assembling individual parts. This benefit also applies to monolithic mechanisms an example of which is given in 4.2.1.5.

The concept of consolidation can extend to building assemblies with moving parts that are already assembled. Fig. 21 illustrates a valve assembly that was manufactured in a single build with no post-build operations. It includes a ball joint to adjust the direction of air flow.

4.3.2 Logistics—There are multiple logistical benefits to using AM:

4.3.2.1 The reduced lead time and absence of tooling presents an opportunity to manufacture parts on demand, giving the following logistical benefits:

- (1) Avoid high minimum order quantity (MOQ).
- (2) Easier coverage of low demand rate (slow moving parts).
- (3) Reduced inventory level.
- (4) Enables remote logistics [that is, repair remote equipment (farm, island, etc.)].
- (5) Reduced distribution costs through Redistributed Manufacturing (RDM).

4.3.2.2 A logistical benefit of manufacturing individualised components:

- (1) Individual marking of parts in the build negates the need for physical tagging of parts (although there may be extra CAD work required to add serialised markings).

4.3.2.3 For the specific case of part consolidation through use of AM, benefits include reductions or simplifications of several aspects:

(1) Maintenance of part numbers is considered a hidden cost of doing business that is, space (physical or memory space); periodic review (labor); part number instigation (assignment, review, testing). With consolidation of parts using AM, the cost of maintaining part numbers is reduced.

(2) Verification and validation of several parts.

(3) Ordering, tracking, warehousing of individual parts.

(4) Notice of Change(s) for parts can come from obsolescence, material change, supplier part number consolidation, supplier design changes. Each Notice of Change takes weeks of work to resolve.

(5) Reliability of 1 part versus reliability of many individual parts.

(6) Service of 1 part versus service of many individual parts.

4.3.2.4 In practice, AM is often chosen because it can give a ‘hybrid’ benefit, for example, an incremental performance improvement with a reduced lead time and a slightly longer service life.

5. Available Materials and Processes

5.1 This section provides information to aid in assessing the technical feasibility of using AM for a product.

5.1.1 AM machines can currently only process a limited number of the materials available in conventional manufacturing. However, there are AM machines available for each of the following material groups:

5.1.1.1 Metals,

5.1.1.2 Polymers and elastomers.



Material:	TPU
Company / credit:	BigRep GmbH
Industry sector:	Any
Why AM was used:	The AM process builds the casing and the liner/inserts simultaneously, replacing the previous chain of manufacturing steps and processes.
Potential secondary benefits:	Data-driven process allows easy adaptation of the case design per shipped component. Supply chain reduction. Reduced shipping container storage.
Which AM process category:	MEX
Other suitable AM process categories:	Any polymer process able to process TPU at the required size.

FIG. 16 Shipping Case (© BigRep GmbH, all rights reserved)

5.1.1.3 Ceramics and glasses, and

5.1.1.4 Biomaterials and organics including paper and foods.

5.1.2 This guide includes information on the first three groups, which are the most mature and widely used in AM. For further information on AM processes, materials and their properties, refer to the ISO/ASTM standards and guides as identified in Section 2.

5.2 Metals:

5.2.1 *Summary of Metal AM Processes*—AM processes for metals create parts from feedstock in powder, wire and sheet form. Consideration of the material availability and storage is therefore important when comparing processes. Some processes use a deposition head that can be mounted onto a robot or gantry, allowing large scale structures; the others require a fixed size chamber or bed so that layers of feedstock or binder,

or both, can be deposited, thus limiting the maximum size of build parts. A third consideration is the method of feedstock consolidation since this is linked to deposition rate and therefore speed of manufacturing. Most metal AM processes currently employ a raster technique to consolidate material. A brief overview of the metal process categories is given in [Table 1](#). Additional information is available in ISO/ASTM 52900 and ISO/ASTM 52910.

5.2.1.1 *Hybrid Metal AM Processes*—To compensate for the relatively rough surface texture produced by metal AM processes, AM machine manufacturers have released hybrid AM hardware, which combine the AM build hardware with CNC machining in the same build chamber. Presently two processes are available:

- (1) PBF – CNC hybrid
- (2) DED – CNC hybrid



Material:	Nylon (PA12)
Company / credit:	Fitz Frames
Industry sector:	Consumer
Why AM was used:	Personalised fit
Potential secondary benefits:	No inventory (manufacturing on demand)
Which AM process category:	PBF-LB/P with post-processing
Other suitable AM process categories:	Any that can meet the required price point

FIG. 17 Personalized Spectacle Frames (© Fitz Frames, all rights reserved)



Material:	CuCr1Zr
Company / credit:	GKN
Industry sector:	Cross-sector
Why AM was used:	Service life increased by a factor of 3
Potential secondary benefits:	Reduced energy consumption due to square cross section of coil
Which AM process:	PBF-LB
Other suitable AM process categories:	The material requirement would currently preclude using other metal AM processes

FIG. 18 Induction Coil (©GKN, all rights reserved)

5.2.1.2 Besides combining AM build and post-process machining in a single step, an added advantage of using a hybrid AM approach is that the component can be machined as the

layers are being created. This enables machined surfaces in